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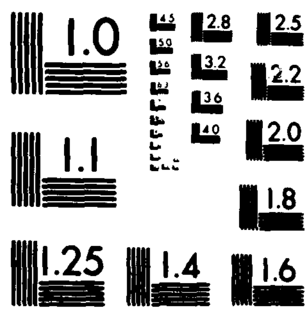

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Superconducting Electronics

Final Technical Report on

ONR Contract No. N00014-77-C-0440

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University of Virginia

Charlottesville, VA 22901

Bascom S. Deaver, Jr.
Professor of Physics
Department of Physics
804-924-3781

Robert J. Mattauch
Professor of Electrical Engineering
Department of Electrical Engineering
804-924-3564

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SUPERCONDUCTING ELECTRONICS

I. INTRODUCTION

This is the final report on research entitled "Superconducting Electronics" carried out under ONR contract No. N00014-77-C-0440 from 1 July 1977 through 31 December 1980. This work has been a collaborative effort of members of the Semiconductor Device Laboratory directed by Robert J. Mattauch, Professor of Electrical Engineering, and of the low temperature physics group directed by Bascom S. Deaver, Jr., Professor of Physics. The objectives of the research have been 1) to design, fabricate, and test Josephson mixers for use at frequencies greater than 100 GHz, 2) to fabricate and characterize various types of microbridges, particularly ones on semiconductor substrates which may exhibit measurable interaction with the substrate and 3) to measure the microwave properties of some NbN SQUIDs. In the ~~following sections~~ we summarize ~~the~~ progress made on all of these topics is summarized and ~~give~~ references to publications reporting the results in more detail are presented.

Briefly the results of the research are as follows: We have fabricated niobium variable thickness bridges on glass, quartz, silicon and GaAs substrates and tested them as microwave mixers at 10 GHz and at 80-100 GHz. At 10 GHz they behaved as almost ideal Josephson mixers, however at the higher frequencies their behavior is dominated by heating effects, although much less so than bridges of uniform thickness. Bridges on silicon substrates showed considerably reduced effects of heating but nevertheless were still dominated by heating. Subsequently we fabricated extremely small area microtunnel junctions to test as Josephson mixers. However during this work it became apparent that SIS mixers were far superior to Josephson mixers and we subsequently turned our attention to fabricating niobium junctions with areas less than 1 μm^2 for use as SIS mixers. This work had just been initiated at the conclusion of the present contract and is being carried on with other support.

We have studied in great detail the structure on the I-V curves of tin, indium and niobium variable thickness bridges on glass, quartz, silicon and GaAs substrates to obtain information about the properties of these bridges and possible interactions with the substrate. We assembled a microcomputer controlled data acquisition system for recording and analyzing the data and were able to study in great detail the variation of the I-V curves and their derivatives as functions of temperature, magnetic field and applied microwave power. As discussed in more detail below there is a profusion of structure that can be understood using various models of the Josephson effects, flux flow and heating effects. In collaboration with the Naval Research Laboratory we have also studied in detail the properties of granular niobium nitride variable thickness bridges and observed microwave response due to the Josephson effect at frequencies up to 40 GHz.

Finally we have begun studying in collaboration with the Naval Research Laboratory some microwave SQUIDs using niobium nitride granular microbridges. These bridges appear to behave as nearly ideal Josephson junctions and give extremely good performance as SQUIDs at 10 GHz.

Each of these topics is discussed in more detail in the following sections.

II. Millimeter Wave Mixing with Nb Variable Thickness Bridges

The high frequency response of metallic superconducting bridges has been shown to be limited by self-heating.[1] However bridges of variable thickness consisting of thin, narrow links joining two much thicker bulk films are less limited by heating than bridges in films of uniform thickness.[2] In order to test their response as millimeter wave mixers we have fabricated Nb variable thickness bridges on fused quartz, silicon and gallium arsenide substrates, and measured their response at 80-100 GHz.

Fabrication

The bridges were of the form shown in Fig. 1 and were located at the center of a microwave choke structure designed to isolate the microwaves from the rf and biasing terminals. Junction fabrication begins with the rf sputtering of a Nb film 500 Å thick on the substrate. The film thickness was determined by measuring its optical density using a laser. The films were deposited at ∿400 Å/min and yielded films with a room temperature to helium temperature resistance ratio of 9. The films exhibited an initial T_c of about 8K although after subsequent processing steps it was decreased to ∿5.5 K.

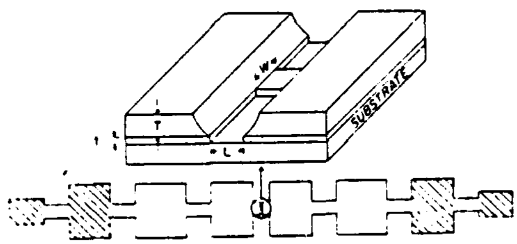

Fig. 1. Bridge and microwave choke. W = 1 μm, L = 0.57 μm, t = 500 Å, T = 5000 Å. The choke structure is Nb with Au pads (crosshatched) overlaid.

A quartz fiber 1 μm dia. was placed across the film and after a sputter etch to clean the surface, a layer of Nb 5000 Å thick was deposited. The quartz fiber was then removed and photolithography and chemical etching were used to define the bridges and then the choke structure. A lift-off technique was used to fabricate the Au pads on the ends of the choke to provide stable contacts to the film. Our masking technique allowed for simultaneous fabrication of 50 bridges. They were separated using a diamond saw giving individual units 0.8 cm long x 0.5 mm wide. The junctions are extremely stable showing no change in critical current upon cycling between room temperature and helium temperatures, and no precautions appear to be necessary to protect them from burn-out.

Measurements of Bridge Characteristics

The bridges were characterized by measurements of I-V and dV/dI vs V and by microwave mixing experiments with measurements of P_{if} vs V. Their resistance ranged from 0.5 to 6 ohms. The critical current varied linearly with temperature near T_c. There was the usual subharmonic gap peak in dV/dI at $V = \Delta(T)/e$ which gave an extrapolated T_c the same as that obtained from critical current data. At low temperature the I-V curves were hysteretic.

Measurements at 9.9 GHz on bridges on fused quartz substrates (Fig. 2) showed Josephson response at harmonics as high as 100-200 GHz and exhibited both Josephson response and bolometric mixing.[3] The peak in dV/dI at V = 430 μV in Fig. 2 indicates the onset of a self-sustaining hot spot[4] and at higher bias P_{if} is due entirely to bolometric mixing and reflects the exponential variation of the critical current with temperature after the hot spot is formed.

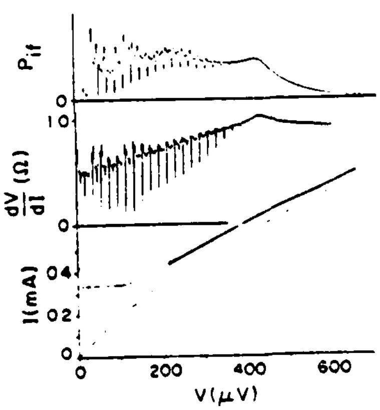

Fig. 2. Data for a bridge on fused quartz substrates showing hysteretic I-V curve without microwaves, and I-V, dV/dI, and P_{if} at 60 MHz with microwave power at 9.90 GHz applied.

The experimental arrangement shown in Fig. 3 was used for testing the bridges at 80-100 GHz. The bridges were mounted in a mixer block specifically designed to obtain a better match to the low impedance bridge. The bridge with

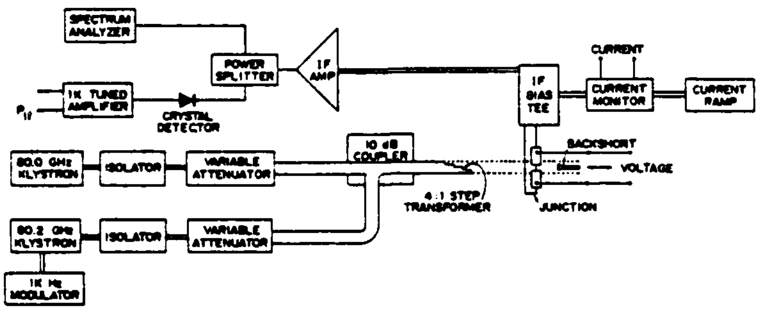

Fig. 3. System diagram for 80 GHz mixing experiments.

its choke was supported in a stripline cavity which positioned the bridge across the height of a quarter-height RG 99 U waveguide. Behind the bridge in the quarter-height guide was a moveable backshort which was adjusted to maximize the power coupled to the bridge.

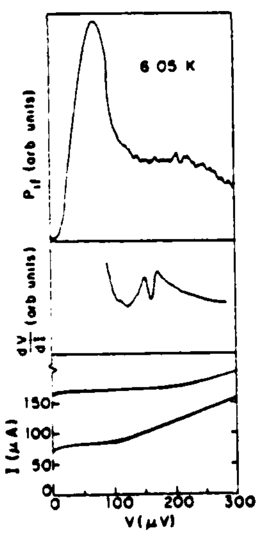

Fig. 4. Data for bridges on Si substrate showing I-V curve with and without microwaves, dV/dI with small Josephson step, and P_{if} at 200 MHz.

No Josephson steps or mixing were found at 80 GHz for bridges on fused quartz although the critical current was depressed at reasonable power levels.

Figure 4 shows data at 80 GHz for a bridge on a silicon substrate. The I-V curve was not hysteretic for the temperature shown. There was a small Josephson step in dV/dI but it was not distinguishable in I-V. The P_{if} curve shows a peak at 83 μV but it is likely to be due to bolometric mixing which also peaks at a maximum in the dynamic resistance.

The response of a bridge on a GaAs substrate to 100 GHz is shown in Fig. 5. Again no steps are distinguishable on the I-V curve but the first step and two subharmonics are visible on dV/dI. This bridge was tested as a mixer at 80 GHz and there was mixing response as before for intermediate frequencies up to 800 MHz.

In all the bridges, hysteretic I-V curves were found above a certain value of I_c. This hysteresis is attributed to the voltage dependence of the critical current resulting from self-heating. The I_cR product at the on-set of hysteresis was found to be larger for junctions with semiconducting substrates.

Substrate	$R_n(\Omega)$	I_cR (at hysteresis)
Fused quartz	1.0	220 μV
Gallium Arsenide	.25	750 μV
Silicon	2.75	1200 μV

The increase in the I_cR product in the silicon substrate bridge would seem to indicate that heating in the bridge is decreased since heat conduction by electrons is 2.75 times less than for the bridge on fused quartz but the I_cR product is increased by a factor of 5. Even though a step transformer was used, there was a large mismatch of the microwave power to these very low impedance bridges and apparently there is extraneous heating throughout the mounting structure. This may account for the dominance of thermal effects in these data.

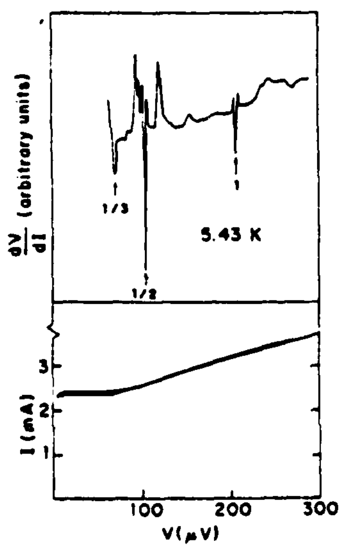

Fig. 5. Data for bridge on GaAs substrate. I-V and dV/dI with 100 GHz microwave applied

These results are reported in the following paper, abstract and Dissertation:

D.W. Barr, R.J. Mattauch, Li-Kong Wang, and B.S. Deaver, Jr., Millimeter Wave Response of Nb Variable Thickness Bridges, in Future Trends in Superconductive Electronics (Charlottesville, 1978), B.S. Deaver, Jr., D.M. Falco, J.H. Harris and S.A. Wolf, Editors, AIP Conference Proceedings No. 44 (American Institute of Physics, New York, 1978), pp. 345-348.

D.W. Barr, Li-Kong Wang, R.J. Mattauch and B.S. Deaver, Jr., Millimeter Wave Response of Niobium Variable Thickness Bridges, Bulletin of the American Physical Society 23, 358 (1978)

Millimeter Wave Response of Niobium Variable Thickness Bridges, Daniel W. Barr, Ph.D. Dissertation, Electrical Engineering, University of Virginia, May 1978.

III. Properties of Variable Thickness Bridges

A. Nb Variable Thickness Microbridges

Superconducting niobium microbridges have appealing properties for application as Josephson devices; however, in common with other thin-film bridges, their high-frequency response is limited by self-heating and various characteristics of their I-V curves can be attributed to thermal effects. Variable-thickness bridges consisting of thin narrow links joining two much thicker bulk films are less limited by heating than bridges of uniform thickness. Bridges of this geometry were originally considered because they more nearly approximate conditions assumed for some calculations of the properties of thin-film bridges and subsequently there have been several theoretical treatments of their characteristics, particularly the transition from Josephson to flux flow behavior.

We have studied extensively the properties of Nb bridges of the kind shown in Fig. 1 originally designed for mixing experiments at 100 GHz.

For testing, a bridge was mounted across a section of X-band waveguide with its height reduced to 0.010 cm in an attempt to better match the low impedance of the bridge. It was placed in a cryostat in which its temperature was controlled to within less than 1 mK. The cryostat was mounted inside double mu-metal shields and a superconducting shield enclosed the region containing the bridge. Bridges were characterized by measurements of the dc I-V curves and dV/dI versus V for various temperatures and incident microwave power levels. They were also tested as microwave mixers using a local oscillator frequency of 9.90 GHz and an intermediate frequency of 60 MHz by plotting the i.f. power P_{if} versus V for various temperatures and local oscillator power levels.

Many bridges were studied and all had some general features. At temperatures within about 0.1 K of T_c these bridges exhibit nearly ideal Josephson characteristics and may be regarded as having uniform depression of the order parameter across the whole bridge. In this range they are relatively efficient microwave mixers and would be expected to function well in other device applications.

At lower temperatures they exhibit single and multiple flux flow corresponding to nonuniform depression of the order parameter. In this range they are much less efficient as microwave mixers but they have extremely reproducible characteristics and should function well in applications that depend only on flux switching.

At temperatures more than a few tenths of a Kelvin below T_c the high-frequency response is limited by self-heating. For improved high-frequency response, smaller better-cooled bridges will be required. Hysteresis of the I-V curves, depression of the energy gap, a feature interpreted as the onset of a self-sustaining hot spot, and bolometric mixing can all be described very well by a simple heating model.

These data and their interpretation have been described thoroughly in the following paper, Dissertation and abstract, consequently we will not repeat that discussion here:

Li-Kong Wang, Dae-Jin Hyun and B.S. Deaver, Jr., Heating and Flux Flow in Niobium Variable Thickness Bridges, Journal of Applied Physics 49, 5602-5609 (1978).

Li-Kong Wang, Superconducting Niobium Variable Thickness Bridges: Char. teristic and Properties as a Microwave Mixer, Ph.D. Dissertation, May 197u.

Li-Kong Wang and B.S. Deaver, Jr., Flux Flow and Heating Phenomena in Niobium Variable Thickness Bridges, Bulletin of the American Physical Society 23, 357 (1978).

B. Studies of Nb and Sn Microbridges by I-V Spectroscopy

A wealth of information about a Josephson junction and its interaction with its surroundings resides in the structure on the I-V curve and the variation with external parameters. However with formerly standard techniques using an x-y recorder, a general scan of the whole I-V curve was made and several subsequent scans with different ranges and gains were required to explore details on various parts of the curve. Thus it was difficult to study small variations in a systematic way. To reduce the difficulty we have assembled a microcomputer-controlled data acquisition system and are using it for I-V "spectroscopy".

A general purpose system based on a DEC PDP 11/03 computer with 28K words of memory has been assembled. Its mass memory is provided by dual floppy disks which store 0.5 M bytes per side. As inputs there are eight differential channels of 3 1/2 digit A to D which can sample at 10 KHz and a 5 1/2 digit system voltmeter which can sample at $\sim$ 200 readings/sec. The voltmeter input is controlled by a scanner which can switch at a rate of 100 channels/sec. The voltmeter and scanner are operated through an IEEE-488 bus input that can handle up to 15 instruments. Also there is a 16 bit parallel input/output port for command and control. A CRT terminal is used for the monitor and for graphics. Additional output is from a two-channel D to A which feeds an x-y recorder. A DEC writer provides typed output and serves as an alternate terminal.

The computer has been programmed in Fortran and two types of software have been created. One is a general purpose data acquisition program that provides control of the instruments and storage of data. The configuration of the experiment can be easily changed at any time, therefore much flexibility is provided. A second program provides interactive graphics for raw data manipulation and configures the data for handling with adjunct programs. This system is dedicated to the study of the characteristics of microbridges and other Josephson devices for this contract. A magnetically and rfi shielded cryostat in a screen room is used for the measurements. The voltmeter and current sources are battery operated and the lock-in amplifier operated from filtered power lines. Outputs from these instruments are taken outside the screen room through rfi filters to the computer which is located outside the screen room so that noise generated by the computer is not coupled to the experiment.

With this system we record in a single slow scan I, V, dV/dI, d^2V/dI^2, and the temperature (which is controlled to within about 1 mK.) We typically record 1500-2000 sets of values of these variables for each scan. The data manipulation program then permits display of any variable plotted versus any other, over the whole range of the variable with arbitrary magnification, any portion of the data. Since the data is taken with high resolution it can be expanded by a large factor before noise is the limitation. The program also provides for reading off selected points from the data already scaled in real units (volts, amps, K, etc.) and makes the data accessible to adjunct programs for computation.

We have studied I-V curves and their derivatives as functions of temperature, magnetic field, microwave power and in a few cases, intensity of optical radiation from a laser. Samples studied include Nb and Sn variable thickness bridges on glass, fused quartz, single crystal quartz, Si and GaAs substrates.

A summary of our results is as follows:

1. Near T_c, Nb and Sn bridges behave like nearly ideal Josephson junctions.
2. At lower temperatures the behavior of these bridges is dominated by flux flow and heating but the bridges on Si and GaAs are much better cooled. A simple heating model accounts systematically for many of the observed features.

3. At high bias currents both types of bridges exhibit a profusion of complicated structure that varies rapidly and reproducibly with temperature [in general more rapidly than $I_c(T)$ or $\Delta(T)$] and that we interpret as the onset of discrete increments of resistance far out into the banks supporting the bridges.

4. At intermediate bias currents we observed features on the Nb bridges that we interpret as the onset of additional flux flow channels. At some temperatures and currents small peaks in the dynamic resistance coalesce and give huge peaks. Similar huge peaks are found to occur when very small amounts of microwave power are applied. These peaks appear to result from synchronized multiple flux flow.

Further evidence for this interpretation is provided by the fact that these are regions of the I-V curve in which the microwave induced steps are spaced at irregular intervals. At special temperatures the step structure is much sharper and the spacing becomes regular but with 2, 3 or 4 times the normal Josephson spacing. Similar effects are found with the Nb N bridges, described below.

These results are reported in detail in the following:

C.H. Galfo, Li-Kong Wang, B.S. Deaver, Jr., D.W. Barr and R.J. Mattauch, Properties of Variable Thickness Bridges on GaAs Substrates, in Future Trends in Superconductive Electronics (Charlottesville, 1978), B.S. Deaver, Jr., C.M. Falco, J.H. Harris and S.A. Wolf, Editors, AIP Conference Proceedings No. 44 (American Institute of Physics, New York, 1978) pp. 349-353.

Christopher H. Galfo, Current-Voltage Characteristics of Superconducting Weak Links in the High Current Regime, Ph.D. Dissertation, May 1980 (completed Sept. 1979).

C.H. Galfo and B.S. Deaver, Jr., Current-Voltage Characteristics of Tin Microbridges on GaAs Substrates, Bulletin of the American Physical Society 23, 357 (1978).

C.H. Galfo, Li-Kong Wang, R.L. Steiner, Dai-Jin Hyun and B.S. Deaver, Jr., Josephson and Nonequilibrium Effects in Nb Bridges, Bulletin of the American Physical Society 24, 265 (1979).

C. Micro-tunnel Junctions

As a potentially attractive alternative to variable thickness bridges for microwave mixing Nb microtunnel junctions with very small capacitance and high-resistance were fabricated. The basic structure of our junctions was a sputtered Nb film over which a layer of borosilicate glass about 1 μm thick is deposited using a silane plus diborane deposition system. Holes approximately 2 μm in diameter with reasonably straight walls were produced by plasma etching through this layer. A tunnel barrier was deposited in the bottom of this hole and a thick Nb film deposited in the top electrode.

This work was reported in "The Microtunnel Josephson Junction", John Upshur and Robert J. Mattauch, Proceedings of the IEEE Region 3 Conference, Southeascon '79, 79 CH 1432-4 (1979).

While this work was in progress it became apparent that mixers using the nonlinearity of the quanparticle current in SIS junctions have greater potential than Josephson mixers. Consequently our efforts were turned just at the end of this contract to building extremely small area (less than 1 μm^2) Nb tunnel junctions. These are being made by sputtering a 1000 Å thick film of Nb on a quartz substrate, covering this film with a thick ($\sim$ 1-2 μm) insulator, ion milling at an angle to the surface to expose a sloping edge, plasma oxidizing the exposed edge of Nb, and finally laying down a 1-μm wide Nb stripe across the slope on the second electrode.

D. Nb N Microbridges

There is considerable interest in high T_c refractory superconducting materials for the fabrication of microwave radiation and magnetic field detectors.[5] The use of these materials should yield devices which are more rugged and durable than devices fabricated from soft materials or mechanical point contacts. A group at the Naval Research Laboratory has reported that granular niobium nitride microbridges when fabricated in the rf SQUID geometry exhibit intrinsic noise characteristics and operate over a wide temperature range below the bridge T_c.[6,7] Because of their near ideal properties in the SQUID geometry, it was decided to evaluate similar devices as microwave radiation detectors.

In collaboration with them we have investigated the microwave response of high resistance granular NbN microbridges with submicron dimensions. Devices with critical currents less than 5 microamps and bridge resistances of the order of 50 ohms have been studied as a function of temperature at both zero and finite voltages. The current-voltage characteristics were measured with various levels of applied radiation in the frequency range 11-40 GHz. For these frequencies, constant voltage-current steps were observed at the Josephson frequency, 2eV/h for low applied voltages, at higher voltages the radiation induced step spacing deviated from that of ideal Josephson behavior. Additional current steps were also observed at temperatures just above the bridge T_c where no finite critical current could be detected. Although these microbridges are sub-micrometer in dimensions they are large relative to the coherence length for NbN which is about 50 Å. Thus the response to applied microwave radiation may be due to vortex motion synchronized by the applied radiation.[8,9] However, the evidence for oscillating steps does not agree with the vortex model.[10] In order to observe this response, the film thickness must be reduced to a thickness less than the grain size which is less than 100 Å.

The thickness of the bridge limits the T_c of the device to a maximum temperature of approximately 10°K to obtain granular behavior for films prepared as described above. The granular nature of the weak link results in a critical current density of the order of 10^5 amps/cm^2 which is approximately 2 orders of magnitude less than that of the starting film. Once the bridge is sufficiently thin to become granular, the individual grains are believed to be electrically isolated but coupled by Josephson tunneling currents. Although the mechanism by which the microwave response of these devices is observed is not clear, these effects have only been observed in those devices which have granular microbridges. This then may suggest that somehow the phase of the individual grains are coupled perhaps by the microwave field and act as a single Josephson junction. Analogous effects have been observed in NbN SQUIDs with microbridges fabricated in the same manner.

These experiments are reported in detail in the following paper:

E.J. Cukauskas, J.H. Claassen, M. Nisenoff, C.H. Galfo, R.L. Steiner and B.S. Deaver, Jr., Josephson Effects in Granular NbN Microbridges in Inhomogeneous Superconductors - 1979 (Berkeley Springs, W.Va.), D.U. Gubser, T.L. Francavilla, J.R. Leibowitz and S.A. Wolf, Editors, AIP Conference Proceedings No. 58 (American Institute of Physics, New York, 1980, pp. 233-238).

IV. Microwave Properties of NbN SQUIDs

Thin film NbN SQUIDs with granular weak links have been shown to have extremely promising characteristics for a variety of applications at both rf and microwave frequencies.[11] These devices have operated at temperatures up to nearly 14 K and function as SQUIDs over a very large temperature range. At 9.4 GHz a sensitivity of 1×10^{-30} joule/Hz has been demonstrated.[12] At 23 MHz measurements of the step rise parameter show that a number of these devices exhibit intrinsic magnetic flux noise.[13,14]

As an outgrowth of their previous work a systematic study of a large number of NbN thin film SQUIDs has been undertaken at NRL. In collaboration with M. Nisenoff and E. Cukauskas at NRL we have made microwave measurements on five NbN SQUIDs with transition temperatures ranging from 5 K to about 14 K. The microwave data have been used to determine the critical current $I_c(T)$, the normal resistance, R_n, and the energy sensitivity of each device. In these preliminary measurements we have identified several temperature regimes which characterize the behavior of the SQUID. These include temperatures corresponding to the onset of superconductivity in the bulk niobium nitride film, a transition interpreted as the onset of SQUID response, the critical temperature T_c as deduced from extrapolating the critical current curve corresponding to the onset of superconductivity throughout the link, and a transition corresponding to the onset of hysteresis in the SQUID response. We have also found systematic variations in the character of the SQUID response in each of these various temperature regimes.

The critical current data and T_c agree well with the data obtained at NRL for these devices at 23 MHz. In addition we are able to obtain values for the normal state resistance, which we find to be typically about 50 ohms, and to identify features which will limit the high frequency response of the devices at frequencies much higher than 9.6 GHz at which these measurements were made. At microwave frequencies these devices also operate over a very large temperature range and have extremely good energy sensitivity.

There is considerable evidence that the NbN weak links are behaving like nearly ideal Josephson Junctions rather than being characterized by flux flow as would be expected because of their very large width with respect to the coherence length. The nearly intrinsic noise behavior observed when operating the devices as SQUIDs at 23 MHz implies a nearly sinusoidal current phase relation rather than a highly reentrant one as would be expected for a flux flow device. Furthermore some direct measurements of the current phase relation by the Cornell group indicate a critical phase angle of approximately $\pi/2$ again implying a nearly sinusoidal current phase relation.[11]

We have now undertaken more extensive measurements of the properties of these NbN SQUIDs under a new ONR contract with the objective of understanding the preformance of these devices as high temperature SQUIDs and of identifying and understanding those properties due specifically to the granular nature of the bridges.

Results of these preliminary experiments are reported in the following paper:

R.L. Steiner, A.P. Flora, B.S. Deaver, Jr., and E.J. Cukauskas, Properties of Thin Film NbN SQUIDs with Granular Weak Links, Proceedings of the 1980 Applied Superconductivity Conference, Santa Fe, N.M., Sept. 29-Oct. 3, 1980. IEEE Trans. Magnetics, MAG-17 841 (1981).

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